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DESIGN CONSIDERATIONS FOR PARTICLE ACCELERATOR CONTROL SYSTEMS

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Introduction

After construction is complete and the initial debugging is achieved the group of scientists which have been so interested in the technical problems of the accelerator will largely have moved into the experimental programs and will not be interested in the day-to-day problems of machine operation. Also, the group of research and development people will have moved on into the development of experimental apparatus. The groups which will now be involved in the machine will be an expansion of the technical specialists, a group of maintenance engineers, a group of electronic technicians and the machine operators. The performance of the machine will be better, and more reliable, if the design group employs techniques with which the operating groups can live comfortably. It helps if the designers will stress simplicity and standard circuit techniques.

Basically a control system is a communication system which couples the operator to the accelerator. It should be consistent with the principles of communication theory. Let us review some of these principles which bear directly on control-system design. They have been applied conscientiously in the telephone industry and we may be able to improve our control systems if we study their techniques.

Principles of Communication

The cost of a communications channel increases with the information capacity of the channel. It is economical, therefore, to restrict transmission to only that which is truly information. By definition, this is only that data which is not known by the receiver. This means that all of the information which is available and significant at the receiver, should be processed locally so that it does not have to be transmitted through the communication channel. For example; consider a bending magnet and its power supply. It is desirable to maintain the magnetic field at a specified value. It would vary because of perturbations on the power line feeding the power supply and by thermal changes in the magnet resistance. These effects can be removed locally if the magnet regulator is located with the magnet power supply. Then the only information which has to be transmitted is the value of field required. If, upon the other hand, the magnet regulator had been located at the transmitter end of the communications channel, all of the information involved in the perturbations would have had to have been transmitted both ways over the communications channel. It is clear that this would have used much more information capacity then the former arrangement and therefore would have raised the cost of the control system.

Let's consider now what is meant by the information capacity of a channel. According to Shannon the information of the channel is defined as $C = \Delta f \log_2 (1 + \frac{S}{N})$

or $C = 3\Delta f \log_{10} (1 + \frac{S}{N})$. To get a feeling for the information capacity of a familiar information channel, consider a twisted pair cable. Such a cable might have a bandwidth of 80 kilocycles and a signal to noise ratio of 40 decibels. Substituting these into Shannon's formula we have $C = 3 \times 8 \times 10^4 \log (1 + 10^4) =$ 960, 000 bits per second. This is the maximum information which can be transmitted over this twisted pair cable. The actual information which can be transmitted depends upon the type of communications system which is used.

In order to use an information channel the information has to be attached to some type of carrier. This is called the process of modulation. It can be classified by three types; first, types with fixed bandwidth and signal to noise ratio, such as amplitude modulation and pulse amplitude modulation. Secondly, types which exchange bandwidth for signal to noise ratio linearly such as frequency modulation, pulse position modulation and pulse duration modulation. Thirdly, those which exchange bandwidth and information capacity exponentially, such as pulse code modulation. This latter type exchanges bandwidth and signal to noise ratio in a particularly favorable way. It comes closest to Shannon's theoretical information capacity of a channel. In order to see how effectively the information capacity increases with bandwidth, consider the case in which the information is coded by means of binary numbers. The information capacity then is proportional to 2^p. Suppose that p is 10 and then is increased to 11. This requires 10% more bandwidth but increased the information capacity by 100%. The 10% wider bandwidth, increases the noise level by 5%. This is clearly a very effective exchange of information capacity and bandwidth.

Next let us consider a multiplex system, from a communications point of view. The two most commonly used types are time division multiplex and frequency division multiplex. The information capacity of the former is limited by the rise and fall times of the switching pulse and by the Nyquist sampling theorem. Consider a channel which has a bandwidth of 1 megahertz. Suppose we use a frame width of 10 microseconds. With this bandwidth we could sample at about a 0.5 microsecond interval so that we could have about 20 sub-channels. Each sub-channel would then be sampled 100,000 times per second. According to the Nyquist sampling theorem, the highest frequency in a sample data system which can be uniquely defined, is that frequency which can be sampled twice per cycle. The highest frequency that could be put down each sub-channel is 50 kilocycles. Our system would permit twenty 50 kilocycles sub-channels to be passed over our 1 megahertz bandwidth.

Now let us compare this with the same channel divided up by means of frequency division multiplex. If we were to divide this into 50 kilohertz channels with a 5 kilohertz guard band between channels we would have 18 single sideband channels. It is apparent that the two systems are approximately equivalent. In practice, however, the components necessary for frequency division are not as readily available as those for time division

Another concept from communications theory is the idea of preparing the information for transmission before it is actually transmitted so that it can be matched to the capabilities of the transmission system. This is one of the roles that a computer can play in an accelerator - while one experimental group is running, a tape can be prepared to set up the accelerator for the next group. When the first group has completed its run, the tape can send the new information through the control system at a rate matched to the information capacity of the control system. Let's consider now the design of a control system. We have two vast technologies to draw from - the communications technology and the computer technology. Both have important roles to play in an accelerator control system. Communications technology is concerned with the transmission of information over noisy channels. Computer technology is concerned with high speed data processing in a quiet environment.

Since computer technology is so familiar to accelerator builders I would like to concentrate on the contributions which might be made by communications technology. What telephone equipment might we be able to use to advantage in our accelerators? Relay techniques have been developed to a high degree for the telephone system. They are highly immune to noise and can be put into operation with a minimum of debugging time. In this respect they are much less costly than electronic techniques. They are also highly reliable. One specific type of relay that appears to have wide application in accelerators is the telephone cross-bar relay. This is a multiple relay having a very large number of positions actuated by two sets of relay coils. A typical cross-bar relay, which I would like to use as an example in this paper, has 10 poles and 120 positions. It is actuated by 12 select coils and 10 hold coils. These select coils can be thought of as being arranged along the Y axis and the hold coils along the X axis. To actuate the relay one hold coil and one select coil must be picked up. The cross point corresponding to these coordinates is then connected, bringing 10 leads through the relay at this point.

By means of a few auxiliary relays the cross-bar relay can be connected in a variety of configurations. For example; used by itself it is a 120 position 10 pole switch. By means of four auxiliary relays it becomes a 1200 position 1 pole switch or with fewer auxiliary relays it becomes a 600 position 2 pole switch.

Conventional relays in multi-pole configurations up to 30 poles are widely used in the telephone industry and there are many accelerator applications of these also.

Another device available from the telephone industry is the touch-tone unit which uses four sets of two-tone groups to produce ten numbers over a single twisted pair. This is a form of multiplexing which is suitable for relay control.

Another multiplexing device is the T-1 carrier equipment which is widely used by the telephone company. This is PCM equipment designed to put twenty-four 2500 cycle channels on a single twisted pair line.

A typical crossbar system suitable for accelerator control is shown schematically in Fig. 1. The control panel has two keyboards. The first is an address keyboard, the second a data keyboard. Each keyboard is four digits wide and is a decimal system. Each crossbar relay is assumed to be of the 1200 point type, i. e. 12 select and 10 hold carrying 10 leads through. Assume that 2 crossbars operate in parallel at each location so that 20 leads are carried through. The primary crossbar would be located in the control room near the control panel and the secondary crossbars would be located at the various remote locations. For example, one crossbar might be in the rf gallery, another might be near the Cockcroft-Walton and ion source equipment, another might be at the linac control area, another at the booster ring rf station and any number at various experimental locations. As shown, up to 100 secondary crossbars could be used. These would have 100 sets of 20 leads each. The 20 input leads of each secondary crossbar is brought back to one of the output connections of the primary crossbar. The input data leads of the primary crossbar is then connected to the data keyboard. Conversion from a decimal system to a four digit BCD system is achieved with a diode matrix located internally in the control panel. The hundred and thousand columns of the address keyboard controls the primary crossbar while the units and tens columns control the secondary crossbar relays. While these are all connected in parallel an auxiliary contact on the primary crossbar applies power to only the secondary crossbar which is being addressed. The system of Fig. 1 will handle up to 99 secondary crossbar locations and therefore will provide data transmission to 9900 pieces of equipment. By installing several crossbar relays at each location and simply connecting the select and hold coils in parallel more leads can be brought through. For example, if five crossbars were installed at each location twenty twisted pairs and five coaxial cables can be carried through. Ten twisted pairs might be used for the BCD data transmission keyboard, the other ten twisted pairs would be available to bring data back to the control room from each of the remote locations, and the five coaxial cables might be used as wide band channels for sending signals in either direction. The bandwidth of each of the twisted pairs would be about 75 kilohertz over a distance of a mile or so and the coax would be about 3 megahertz.

With this system any number of control panels can be used and a computer may be substituted for one of the control panels.

The switching speed of crossbar relays is about 75 milliseconds so a computer can set up the receiving devices at the rate of about 13 per second. To set up 9,900 pieces of receiving equipment would require about 13 minutes. However, very rarely would one have to actuate that much equipment. Most often it would be a few hundred devices.

There are two types of receiving device that are needed. One is a digitally operated regulator reference to be used to control magnet power supplies, high voltage power supplies, and servo systems for positioning beam probes, TV cameras, etc. The other receiving device is simply a circuit which picks up a power type relay on a given number input. This can be used for turning equipment on and off and for numerical control of function generators, programmers, etc.

Some of the more common read-back devices which can be coupled through this crossbar system are digital voltmeters with BCD outputs and transductors for reading voltages and currents while providing ground loop isolation.

When a computer is connected in place of one of the control panels it has exactly the same access to equipment of the accelerator that the operator has. It can be programmed to scan through the machine and record the status of all of the equipment which has digital readout. It can then be programmed to reset the accelerator to any previous run which has been recorded in its memory. Computer optimization techniques would simply await the ingenuity of the operator.

Conclusion

Accelerator control systems fit both computer technology and communications technology. Some lend themselves best to high speed electronic pulse techniques the others to passing information through noisy channels. The control system designers should keep in mind the significant principles of communication, the switching speed requirements, the importance of electrical noise isolation and the interest, capability and viewpoints of the operating staff which will care for the accelerator through most of its life.

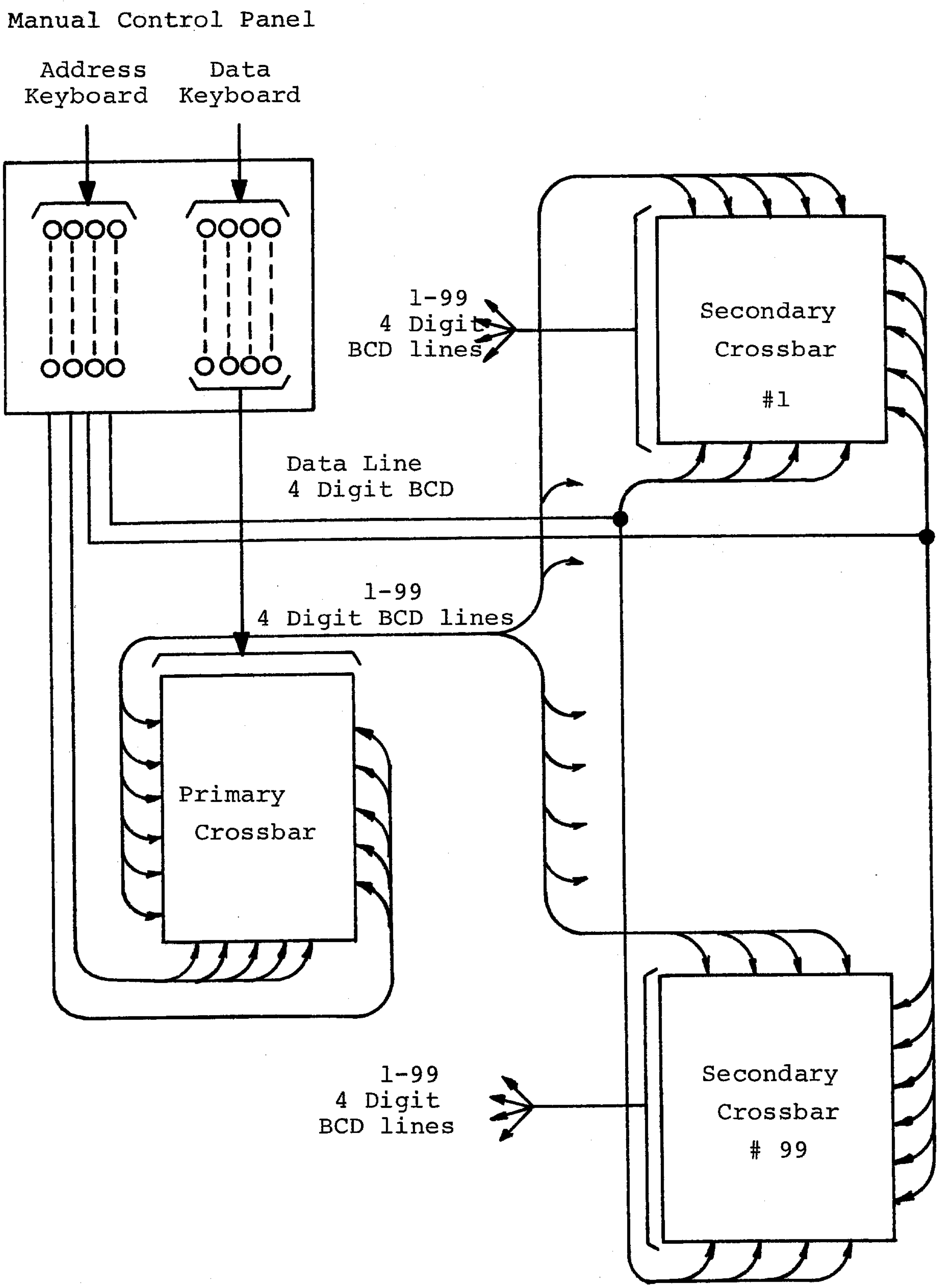
Manual Control Panel
Address Keyboard
Data Keyboard
1-99 4 Digit BCD lines
Secondary Crossbar #1
Data Line 4 Digit BCD
1-99 4 Digit BCD lines
Primary Crossbar
1-99 4 Digit BCD lines
Secondary Crossbar # 99

Figure 1